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XM982 155-mm Artillery Projectile Container Support System: Finite-Element Model Development and Analysis

by Michael Minnicino

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14. ABSTRACT
The XM982 Excalibur container support system is intended to protect the Excalibur munition during transportation by mitigating shock and vibration loadings in addition to performing other functions such as supplementing insensitive munition capabilities. The development of a finite-element (FE) model is a valuable tool for investigating design modifications to the container-foam support system without the need for expensive experimental tests. The FE model facilitates the determination of any design issues and provides insight for future design iterations. The FE model also enables the estimation of the loading conditions the Excalibur munition experiences during drop and vibration events. The focus of this report is the container-munition system response due to container-base-down (CBD) drop events as specified by International Test Operations Procedure. Of the CBD drop events, the 2.1-m CBD, commonly called the 7-ft CBD drop, test is considered the most severe and is investigated in this effort. The developed FE model results compares well to experimental data only after significantly altering the foam stress-strain curves to account for the strain-rate effects.

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1. Introduction

The XM982 Excalibur container support system shown in figure 1 is intended to protect the Excalibur munition during transportation by mitigating shock and vibration loadings in addition to performing other functions such as supplementing insensitive munition capabilities. The development of a finite-element (FE) model is a valuable tool for investigating design modifications to the container-foam support system without the need for expensive experimental tests. The FE model facilitates the determination of any design issues and provides insight for future design iterations. The FE model also enables the estimation of the loading conditions the Excalibur munition experiences during drop and vibration events. The focus of this report is the container-munition system response due to container-base-down (CBD) drop events as specified by the International Test Operations Procedure (*1*) The commercial FE software LS-DYNA is used for the drop simulations (*2*).

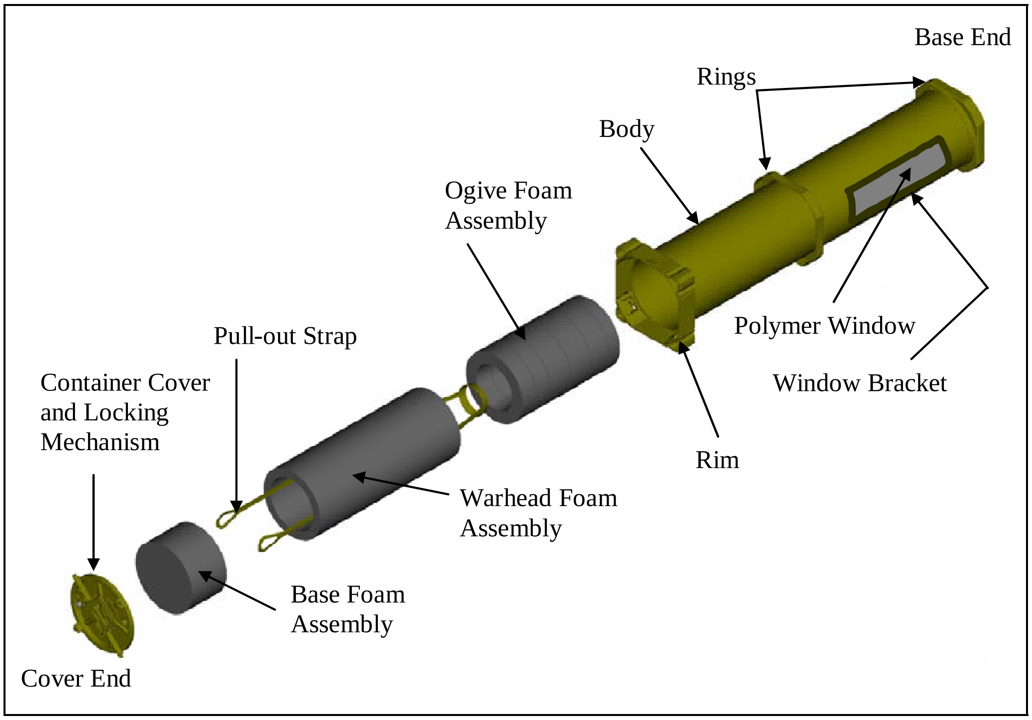


Figure 1. Excalibur container support system solid model.

2. Three-Dimensional (3-D) Model Development

The analysis of the container system during the 7-ft CBD drop orientation is the primary objective of this effort, since prior experiments indicate this orientation has the highest

probability for the munition to impact the container and become damaged. The FE model uses quarter symmetry, thus allowing a more computationally efficient analysis of the CBD drop orientation. The full and quarter-symmetric FE models are shown in figures 2 and 3, respectively. The new 44.5-in container FE mesh is adapted from the previous 49.79-in container FE mesh. The foam system of the FE model is created independently using drawings received from the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) located at Picatinny Arsenal, NJ. The munition FE mesh is identical to the munition mesh of the 49.79-in container configuration FE model.

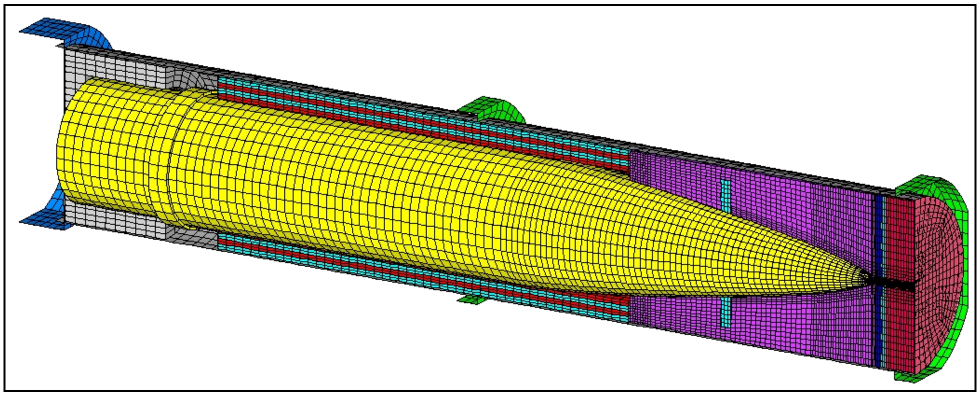


Figure 2. Cross section of the full FE model.

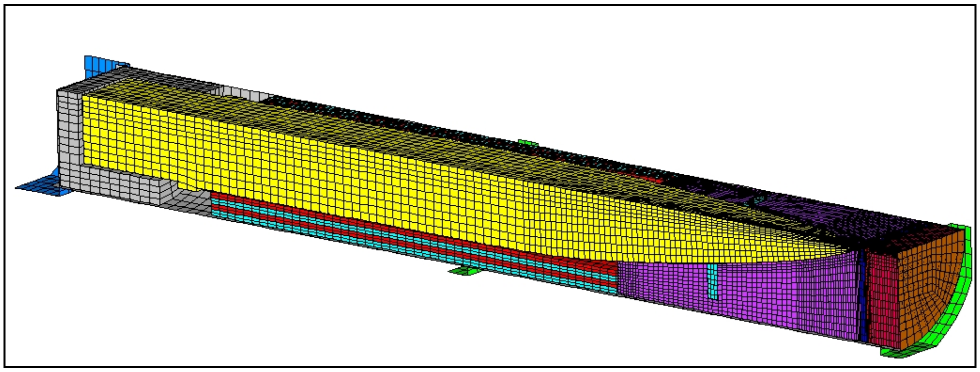


Figure 3. Corresponding quarter-symmetric FE model.

The defeatured container FE model, figure 4, does not include the container windows, window brackets, fasteners, nor cover locking assembly. The complex stamped geometry of the container cover is modeled as a simple circular plate with a uniform 0.060-in thickness (figure 5). Since the simulation effort focuses on the 7-ft CBD drop and the container cover is distant relative to the area of interaction, it is assumed that the container cover has little effect on the event. The window and window brackets were not included in the FE model due to their geometric complexity in addition to unknown window material properties. From the previous 49.79-in container FE analyses, it was observed that omission of the windows is an adequate

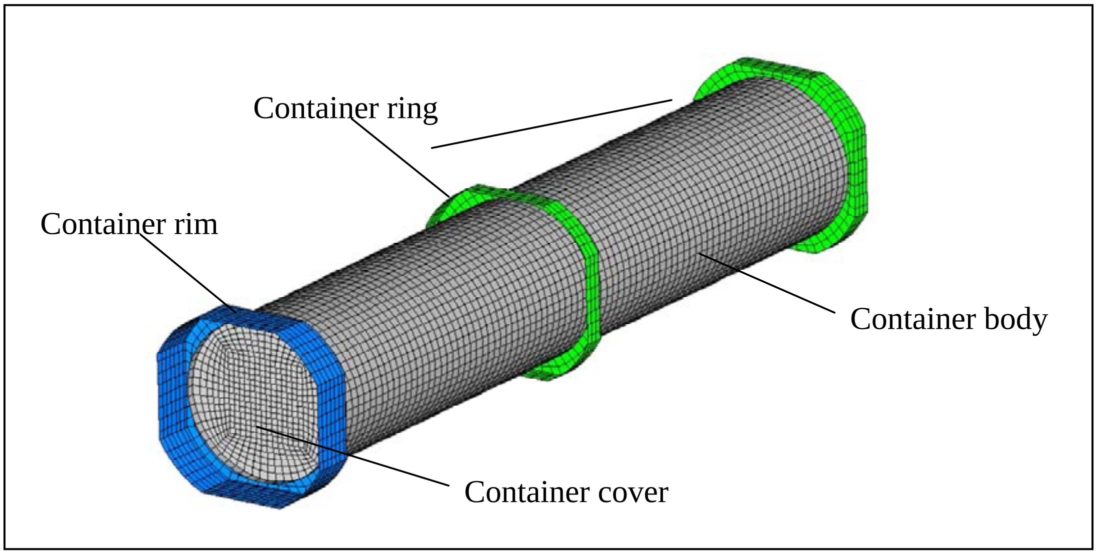


Figure 4. Container FE grid and anatomy.

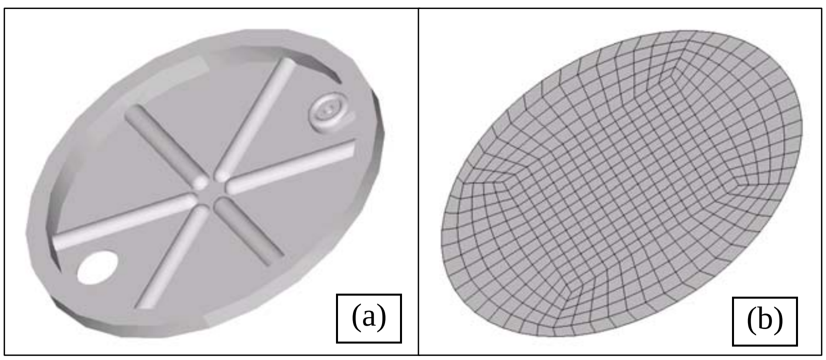


Figure 5. Cover (a) solid model geometry and (b) corresponding FE grid.

assumption for CBD drops as the results matched well with the experimental data (*3*). The container mesh is created on the corresponding mid-surfaces of the solid-model. The container is modeled with shell elements and has a uniform thickness of 0.060 in. This uniform thickness does not capture the thickness increase of the container body at the rim and ring attachments but is a reasonable approximation since the increase in thickness has an insignificant effect on the load experienced by the munition during the impact. The container is modeled with shell elements with an elastic-plastic kinematic hardening material model, LS-Dyna material model *MAT_ELASTIC_PLASTIC. The shells have the appropriate thickness values except at the ring and rim "attachment flanges" where the rim and rings are affixed to the container body. The container material properties are listed in table 1.

Table 1. Container material properties (plain mild steel).

Property	Value
ρ	7.25 E-04 lb-s^2/in^4
E	3.00 E+07 psi
ν	0.3
σ_y	4.00 E+04 psi
E_{tan}	2.01 E+05 psi

The foam-projectile slug assembly is modeled using hexahedral (brick) elements. A cross section is shown in figure 6. The foam is modeled using LS-Dyna's *CRUSHABLE_FOAM material model. This material model behaves like a nonlinear elastic-plastic material constitutive model in that it does not unload to zero strain, but rather to an effective plastic strain. This is because the crushable foam material model unloads at a rate equal to the largest modulus in the stress-strain curve. Due to this experimentally unmeasured behavior, the solution is questionable after the projectile reverses direction (i.e., crosses zero velocity) and the foam begins to unload.

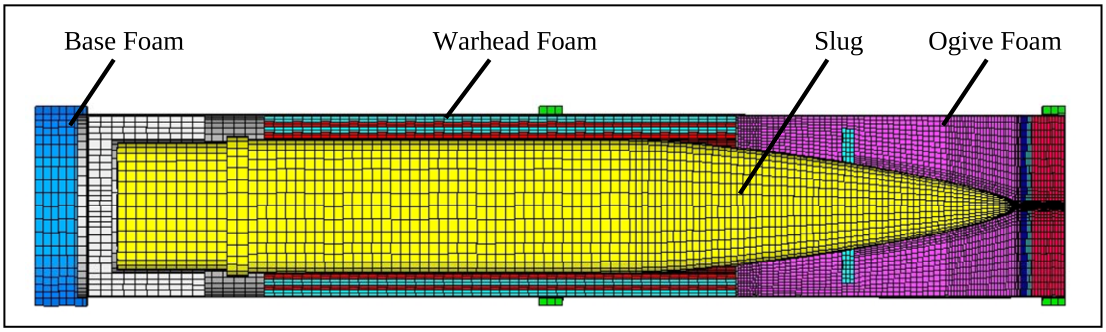


Figure 6. Slug-foam system cross section and anatomy.

The ogive foam assembly shown in figure 7 consists of (from left to right) 9-lb foam, 20-lb foam, HDPE, and 9-lb foam oriented in its extruded direction relative to the container centerline axis. The foams are assumed to be homogeneous orthotropic materials; however, only the extruded direction is distinguished from the remaining two orientations due to its relatively larger increased stiffness (*4*). Additionally, there is a HDPE annulus located on the munition ogive for the purpose of transferring the load to the 9-lb foam at a location away from the sensitive and highly-stressed section due to the CBD drops on the munition nose. The Warhead foam assembly consists of alternating annuluses of 6-lb foam and HDPE as shown in figure 8.

The foam is orthotropic; however, the *MAT_CRUSHABLE_FOAM material model is the constitutive law for an isotropic material. Therefore, the dominate properties of the foam relative to the load direction are used to represent the isotropic response of the foam. For example, the extruded 9-lb foam found between the HDPE plate and the container bottom is modeled as if it is isotropic with properties of the extruded direction. The parameters used for the HDPE and foam material models are listed in table 2.

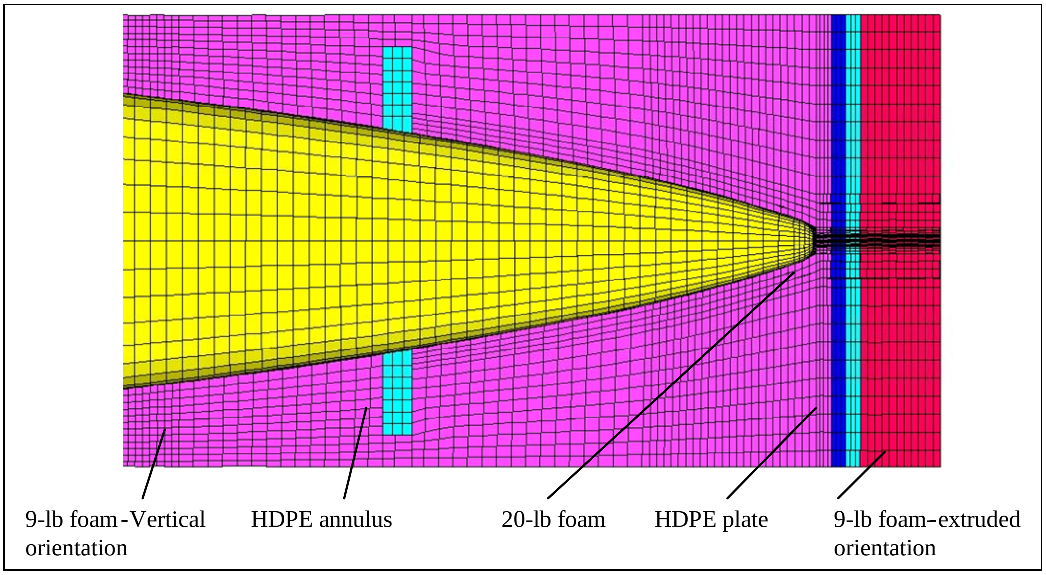


Figure 7. Detailed anatomy of ogive foam system.

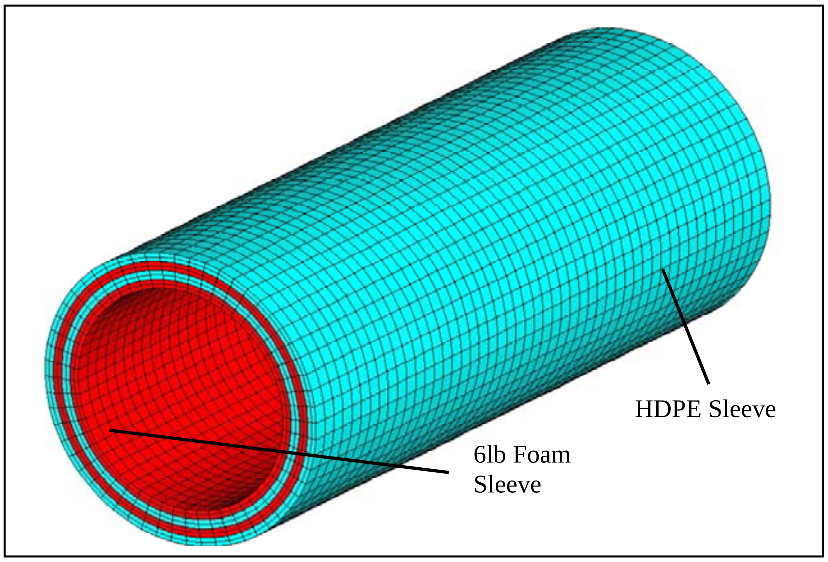


Figure 8. Detailed anatomy of warhead foam.

The slug used in the drop tests is aluminum and is machined to have the profile of the Excalibur munition. Additionally, the slug is ballasted to have the same mass properties as the Excalibur munition. The FE mesh of the slug nose is shown in figure 9. The projectile “slug” is modeled as a rigid body with the properties of aluminum using LS-Dyna’s *MAT_RIGID material model. This was done to easily specify the body’s mass properties, e.g., its center of gravity, translational mass, and principal moments of inertia. As an additional benefit, the rigid body assumption also improves computational efficiency. If the slug is modeled as a deformable aluminum body, the time-step may be limited by the small hexahedral elements in the nose of the slug as shown in figure 9, which results in a longer run time. Lastly, this rigid body assumption

Table 2. HDPE and foam material properties.

Property	Value
(a) HDPE	
ρ	8.97 E-05 lb-s^2/in^4
E	3.00 E+05 psi
ν	0.33
(b) Foam 6 lb	
ρ	9.00 E-06 lb-s^2/in^4
E	1.00 E+05 psi
ν	0.01
Stress-strain curve: modified 6 lb (original 9-lb stress-strain curve)	
(c) Foam 9 lb	
ρ	1.35 E-05 lb-s^2/in^4
E	8.00 E+03 psi
ν	0.01
Stress-strain curve: modified 9 lb	
(d) Foam 9 lb extruded	
ρ	1.35 E-05 lb-s^2/in^4
E	5.50 E+04 psi
ν	0.01
Stress-strain curve: modified 9 lb extruded	
(e) Foam 20 lb	
ρ	1.35 E-05 lb-s^2/in^4
E	5.50 E+04 psi
ν	0.01
Stress-strain curve: modified 20 lb	

is reasonable since relative to the foam, the aluminum slug is approximately rigid. This implies that the internal strain energy stored by deformation of the slug is negligible in comparison to the strain energy stored in the rest of the system. The material parameters for this rigid material model are listed in table 3.

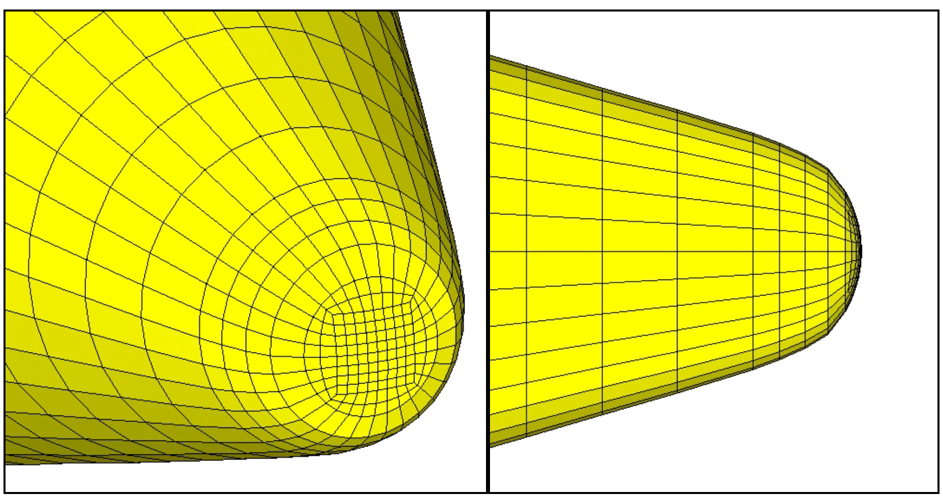


Figure 9. Slug nose (a) perspective view and (b) side view.

Table 3. Slug material properties (aluminum).

Property	Value
ρ	2.59 E-04 lb-s^2/in^4
E	1.00 E+07 psi
ν	0.3
X_c	22 in
Y_c	0 in
Z_c	0 in
T_m	2.72 E-01 lb-s^2/in^4
I_{xx}	1.37 lb-s^2/in^4
I_{xy}	~0 lb-s^2/in^4
I_{xz}	~0 lb-s^2/in^4
I_{yy}	21.5 lb-s^2/in^4
I_{yz}	~0 lb-s^2/in^4
I_{zz}	21.5 lb-s^2/in^4

3. Foam Material Model and Properties

Initial foam material properties were obtained from Dow Chemical's customer support group (*4*). Dow Chemical supplied the load-displacement and stress-strain curves for the Ethafoam HS 900 tested at room temperature, 70 °F (23 °C), at a crosshead rate of 39.37 in/s (1.0 m/s). Additionally, Dow provided a table consisting of five data points along these curves.

The foam material was modeled in LS-Dyna using the *MAT_CRUSHABLE_FOAM constitutive model (*2*). The necessary material properties for this constitutive model for a given temperature are

- density,
- Poisson's ratio,
- stress-strain curve,
- modulus of elasticity (initial), and
- tensile strength.

The Dow information provides density, tensile strength, and a limited number of stress-strain curve data points, all of which are at room temperature. In order to adequately characterize the foam, in-house material testing was conducted to determine the foam's compressive stress-strain curves at 170 °F (77 °C), –60 °F (–51 °C), and 70 °F (21 °C) (*5*). Poisson's ratio could not be determined due to the porosity of the foam, so a value of 0.01 is assumed in the following analyses. This Poisson's ratio value was obtained from reference (*6*), which has data for similar foams. Also, a small parametric study was conducted in which the Poisson's ratio was varied from 0.01 to 0.10 and was found to have little influence on the foam response (*7*).

The average 9-lb and 9-lb extruded foam stress-strain curves for all temperatures are shown in figure 10. The stress-strain curves agree with intuition since the cold curves have both a larger initial modulus of elasticity and yield strength than compared to curves obtained at warmer temperatures. Notice for the room temperature curves that the 9-lb foam stress-strain curves agree well with the plotted Dow data points. Two strain rates were used to load the foam specimens: a slow strain rate of 2.1 m/m-s and a higher strain rate of 18-30 m/m-s.

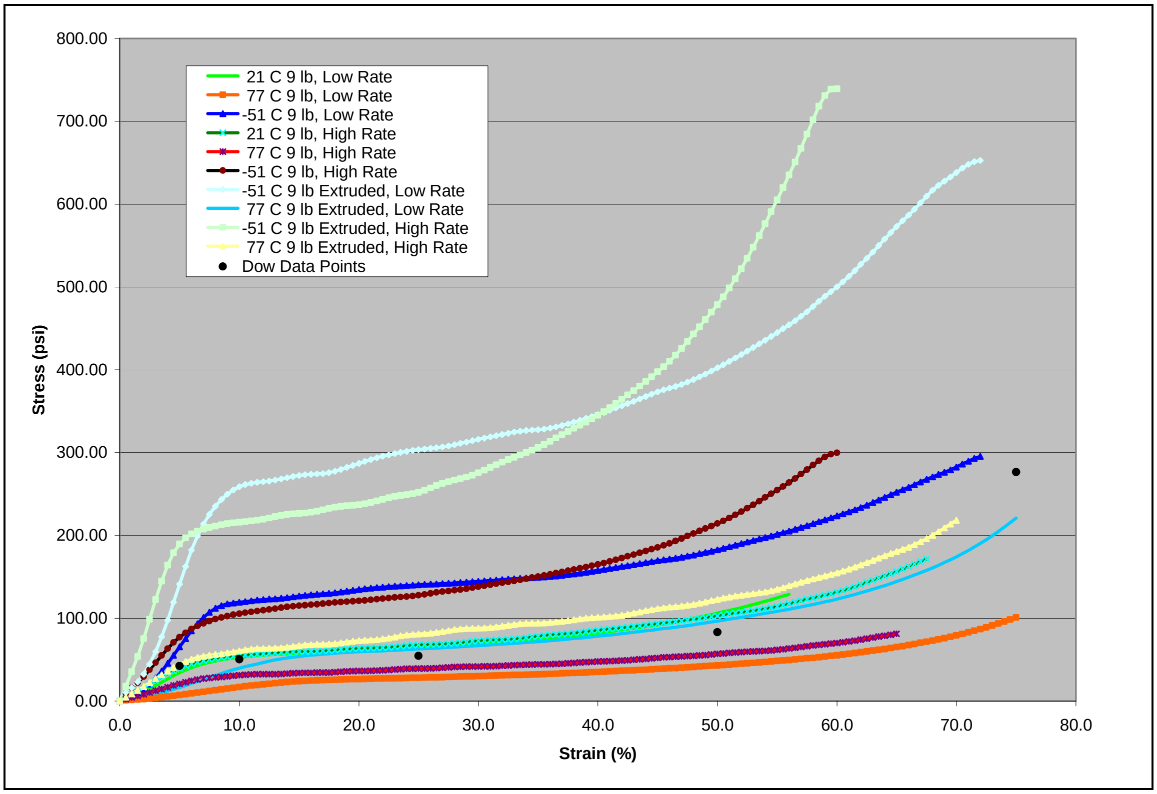


Figure 10. The 9-lb foam stress-strain curves at various temperatures and rates (vertical orientation).

4. Drop Simulation

4.1 Initial Condition Setup

The FE model is setup for a 7-ft CBD drop simulation using the cold foam material properties. The drop simulation is formulated as an initial velocity problem since the response before impact is irrelevant and its calculation is unproductive. To calculate the relevant impact response, the model is defined so the container system is slightly offset (0.005 in) from a user-defined rigid surface at a user-defined orientation with a uniform initial velocity as illustrated in figure 11. Gravity is not included in the analysis. However, the initial impact velocity is determined by considering gravity and the drop height. Thus, the effect of gravity on the rebound of the container is not considered. For the impact event, this is acceptable. The model is conservative

since it does not include friction. Friction is not included because the appropriate foam-aluminum coefficient of friction value is unknown. This model represents a worst-case scenario since the inclusion of friction between the slug and foam will increase the dissipation of energy and reduce the overall displacement of the slug. The initial impact velocity is determined by considering conservation of energy

$$mgh = {}^{1}/_{2}mv^{2} \text{ or } v = \text{sqrt}(2gh), \tag{1}$$

where v is initial impact velocity, m is the system mass, g is gravity, and h is the drop height. For example, a 3-ft drop results in an initial impact velocity of 167 in/s.

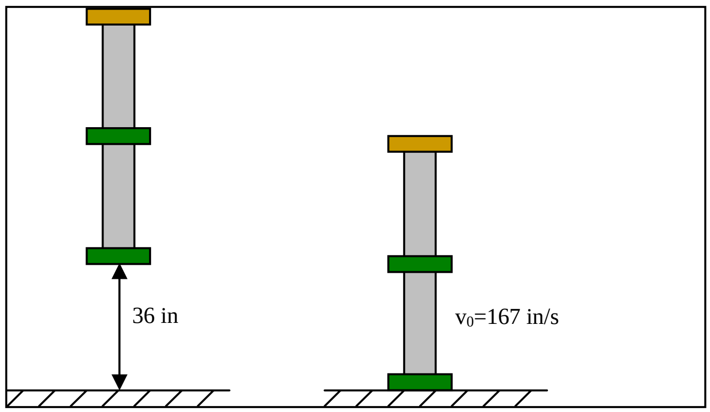


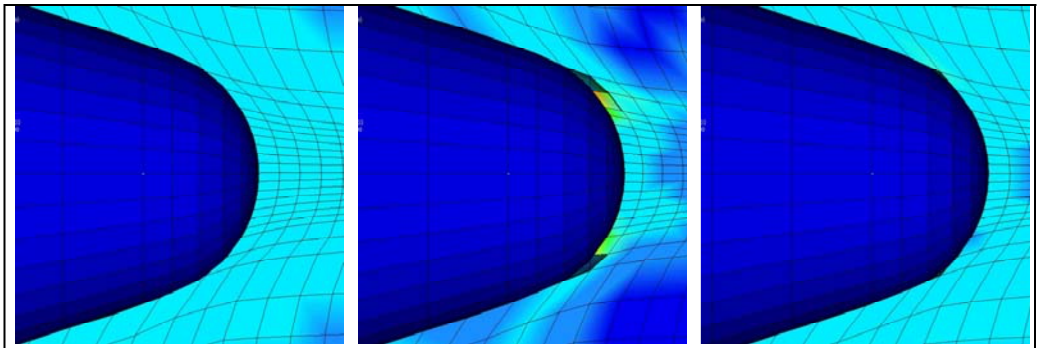
Figure 11. Initial velocity problem setup.

4.2 Large Deformation Considerations

Difficulties are encountered when simulating a CBD drop test due to excessive distortion of the ogive foam elements located near the slug nose. These difficulties are the result of the foam being relatively soft (see Foam Material Model and Properties section). At low-to-moderate strain rates, the 9-lb foam does not begin to significantly resist compressive load until a compressive strain of ~0.85. At these large strains, the FE mesh can become severely distorted, which causes numerical issues in the solution. Thus, in order to capture the foam deformation, a very fine mesh is needed to alleviate or prevent element distortion. The avoidance of severe element distortion is important for three main reasons. First, severe element distortion causes the Jacobian to approach zero, and results in a runtime error, causing the solver to halt. Secondly, excessive element distortion causes contact definitions between entities to become ineffective (loss of contact), thereby enabling the slug to move freely into the ogive foam region where the elements are highly distorted. The third reason is that severe element distortion causes the elements critical time-step to become very small, resulting in longer run times.

A simple and often utilized method to prevent element distortion is to remove, or erode, elements prior to the elements reaching a highly distorted state. The FE erosion sequence is shown in figure 12. Although this method can conserve energy at the cost of computational efficiency, it was implemented in this analysis such that the eroded element and its associated mass and

energy are omitted. Therefore, once an element meets or exceeds a user-defined failure criteria, the element has no further effect on the subsequent system behavior. For light and relatively slow moving materials, such as the foam, omitting the mass and energy loss is a reasonable approximation. The 9-lb extruded direction foam material was not permitted to erode. It is observed that element erosion allows the simulation to reach completion, and the results appear reasonable during the compression phase of the impact event. The erosion parameters are listed in table 4.



t_{i-1} (a) t_i (b) t_{i+1} (c)

Figure 12. Element erosion process that creates spurious peaks in acceleration data: (a) before erosion, (b) time-step before erosion, and (c) new contact surface at time-step after erosion.

Table 4. Erosion parameters.

Property	**Value**
Foam 9 lb	
σ_{vm}	2000 psi
ε_1	—
τ	—
Foam 9 lb extruded	
σ_{vm}	—
ε_1	—
τ	—
Foam 20 lb	
σ_{vm}	45 ksi
ε_1	0.5 in/in
τ	1.95 in/in

Also, interior contact was implemented to further improve the element behavior under large deformation. Interior contact is a new type of contact model in LS-Dyna version 970 specifically developed for enclosed foams (*2*). Interior contact attempts to prevent highly localized element distortion by creating additional contact surfaces within each element. For soft material slave elements, such as the foam, traditional contact loading will significantly deform the slave

element closest to the master contact element and leave interior slave contact elements virtually undeformed. However, using interior contact surfaces effectively distributes the contact load to the adjacent slave contact elements. This contact is seen to help prevent element distortion and is used in the analyses. See reference (*2*) for more information.

4.3 Results

Drop tests were conducted at ARDEC and the results are presented in Bahia et al. (*8*). The cold 7-ft CBD drop experimental acceleration-time histories of the slug at the Fuze Safe and Arm (FSA) and Inertial Measurement Unit (IMU) are shown in figure 13, measured with Endevco accelerometers models 7259 and 7270, respectively. The source of high-frequency content in the acceleration-time histories is unknown. Simple rigid body momentum calculations reveal that the peak acceleration is ~66-131 G, depending on the assumed waveform shape (square, half-sine, or triangular waveforms). The acceleration-time histories are subsequently digitally low-pass filtered using a 4th-order Butterworth filter with a cutoff frequency of 1.5 kHz. The filtered acceleration-time histories are shown in figure 14. The FSA and IMU have peak accelerations of ~110 G and 140 G, respectively, and are in the range of the expected peak values based on simple momentum calculations.

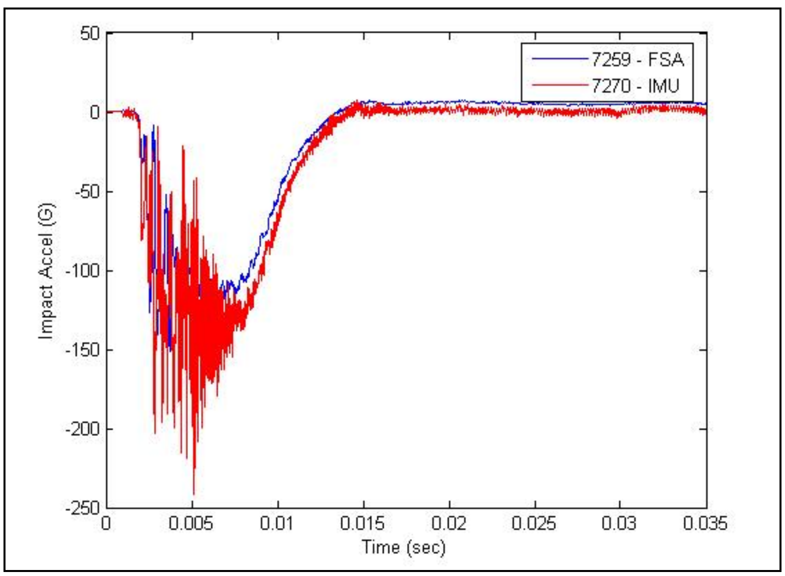


Figure 13. Unfiltered axial-direction projectile acceleration measurements for cold 7-ft CBD drop.

For the quarter-symmetry model results, the rigid slug maximum displacement is 1.350 in. The projectile crossed zero velocity at ~8.2 ms. The maximum deceleration of the projectile is about 138 G. The simulated rigid body acceleration-time history for the slug is shown with the experimental plots in figure 14. The modified foam stress-strain curves (6-lb foam stress-strain curve is not modified), relative to the experimentally determined stress-strain curves, that are used to get the acceleration-time history are shown in figures 15–17. The primary reason the stress-strain curves are significantly different from their original curves is due to the foam’s

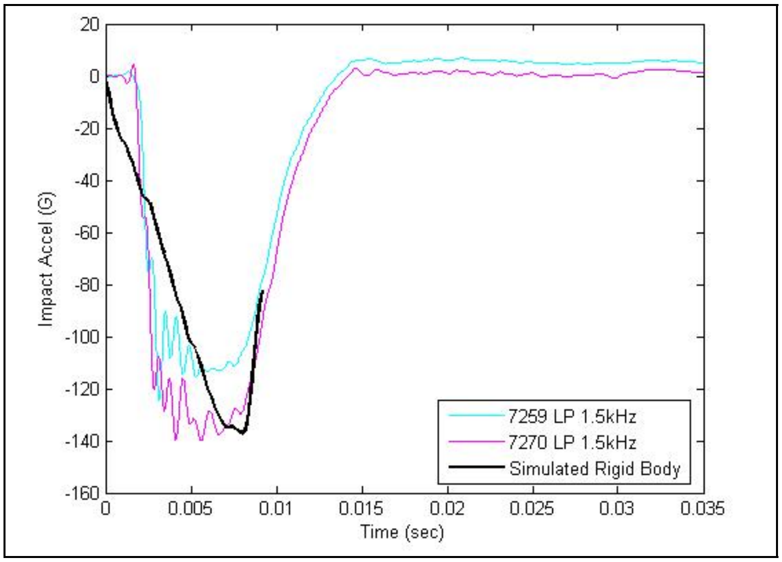


Figure 14. The 1.5-kHz low-passed axial-direction projectile acceleration measurements and simulated response for 7-ft CBD drop.

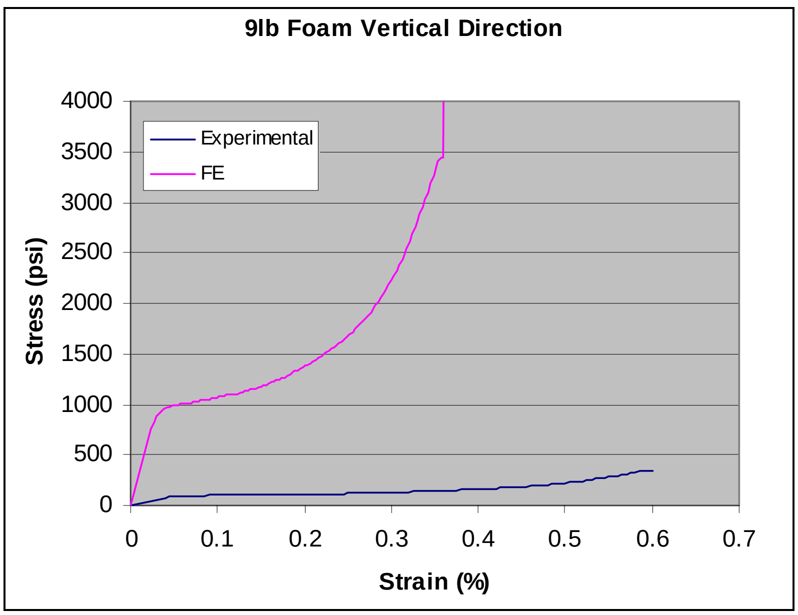


Figure 15. Experimentally measured stress-strain curves comparison with modified stress-strain curves to get presented results for 9-lb vertical direction foam.

strain-rate dependence and the lack of stress-strain curves at the strain rate of the drop event—LS-Dyna predicts a strain-rate, given the modified stress-strain curves, of approximately an order of magnitude higher than the tested 20–30 m/m-s for most of the foam system and a strain rate of several hundred for the foam near the slug nose. Lack of real stress-strain curves at these high strain-rates prevents accurate simulation of the drop event. Lastly, a cross section of the ogive foam is after a 7-ft drop test is shown in figure 18(a). The quarter-symmetric cross section of the

ogive foam of the simulation is shown in figure 18b at maximum displacement. The net ogive foam system deformation is seen to be similar to the simulated maximum displacement as shown in 18c.

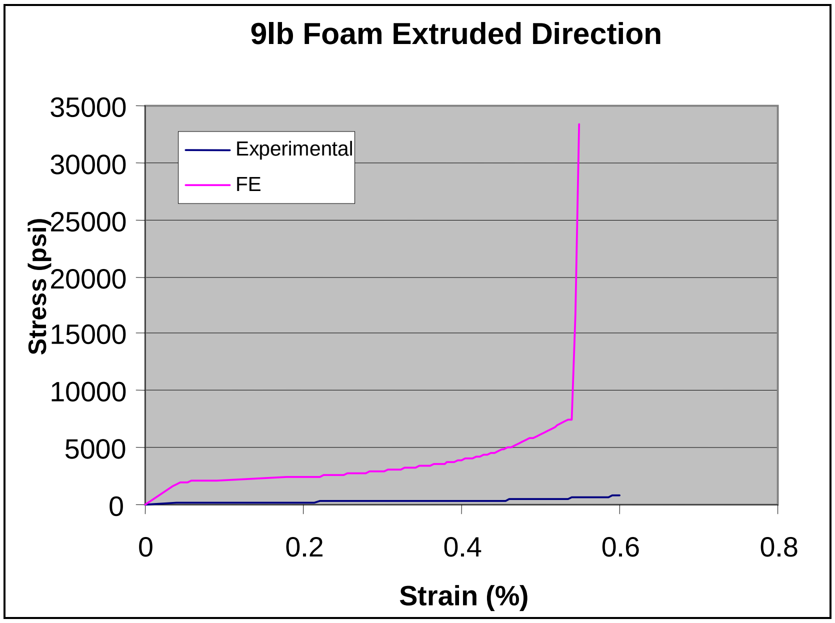


Figure 16. Experimentally measured stress-strain curves comparison with modified stress-strain curves to get presented results for 9-lb extruded direction foam.

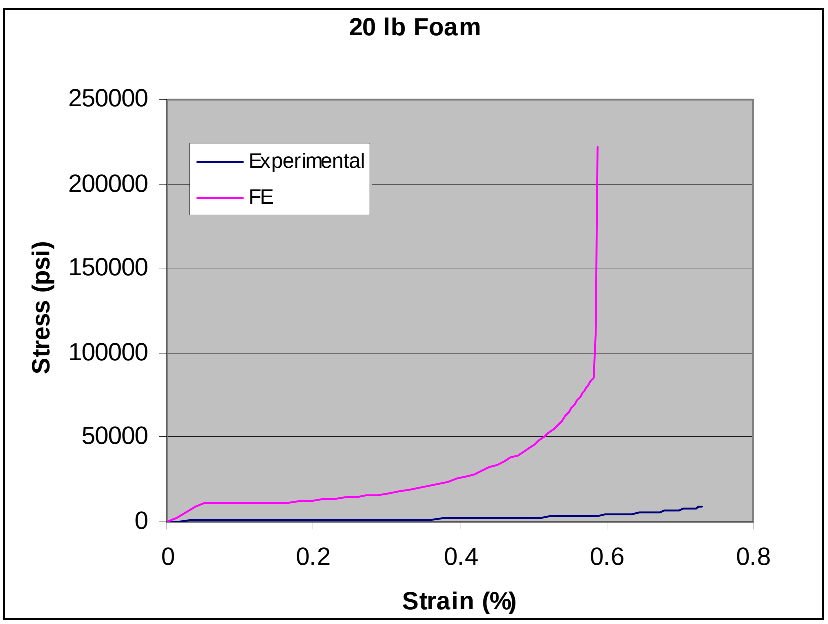


Figure 17. Experimentally measured stress-strain curves comparison with modified stress-strain curves to get presented results for 20-lb foam.

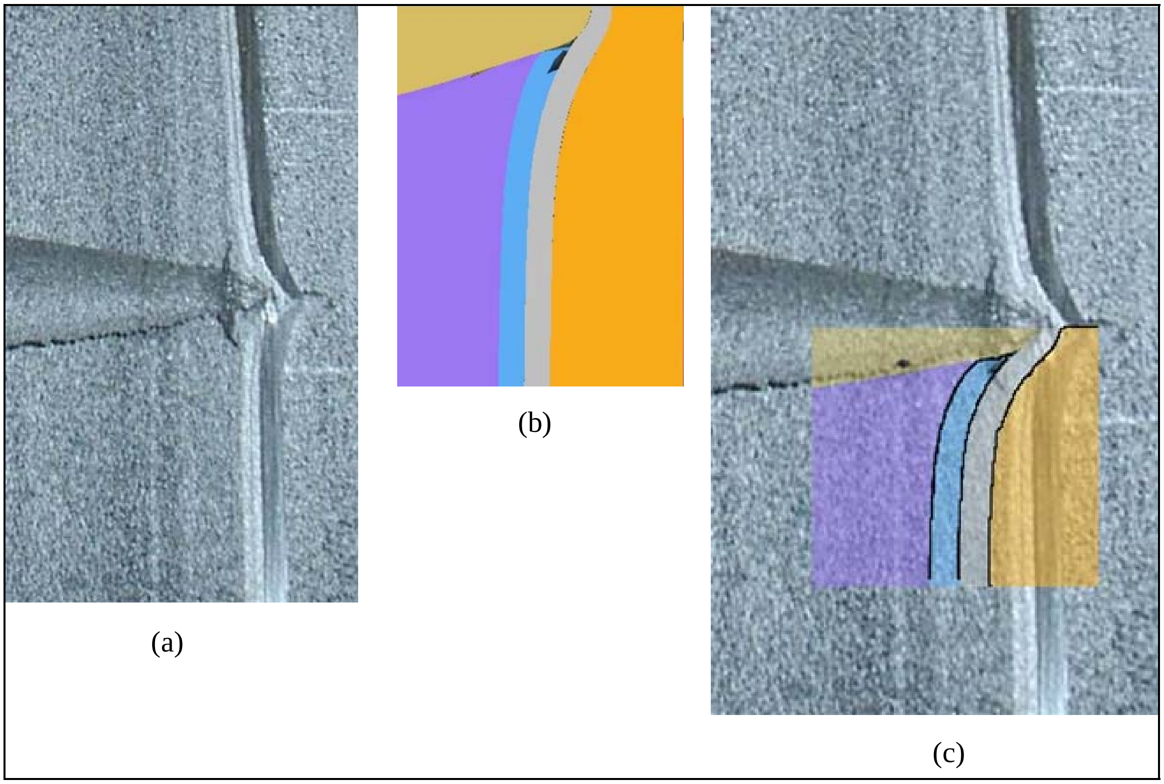


Figure 18. Comparison of (a) experimental ogive foam after 7-ft CBD test to (b) simulated ogive foam at maximum displacement. (c) Experimental and simulated results overlaid for qualitative comparison.

5. Conclusions and Recommendations

The 3-D quarter-symmetric FE model is developed in addition to the full 3-D FE model in LS-Dyna for the drop simulations. The quarter-symmetric FE model was developed for quicker solution times. The quarter-symmetric model can be used only for symmetric loading conditions: nose-down and base-down orientations. The symmetric loading condition assumes that the container perfectly impacts the rigid surface. The full FE model is required for horizontal, diagonal, and edgewise (nonsymmetric) oriented simulations.

The 7-ft CBD drop simulation compares well to experimental data only after significantly altering the foam stress-strain curves to account for the strain-rate effects. To better predict the system response, the foam behavior at these high strain-rates is required. It is recommended that the full-field behavior of the system be determined during the drop event as the acceleration-time histories do not provide a unique solution. This may be achieved by using photogrammetry and removing a pie or wedge-shaped volume from the container-foam to allow for visual inspection of the slug-foam behavior during the drop event.

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